Title	Effect of Additional Element on Weld Solidification Crack Susceptibility of Al-Zn-Mg Alloy (Report III) : Enhancement of Beneficial Effect of Zirconium on Improvement of crack susceptibility by Application of Electromagnetic Stirring(Materials, Metallurgy & Weldability)
Author(s)	Matsuda, Fukuhisa; Nakata, Kazuhiro; Tsukamoto, Kenji et al.
Citation	Transactions of JWRI. 1984, 13(1), p. 57-66
Version Type	VoR
URL	https://doi.org/10.18910/6498
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Effect of Additional Element on Weld Solidification Crack Susceptibility of Al-Zn-Mg Alloy (Report III)†

–Enhancement of Beneficial Effect of Zirconium on Improvement of crack susceptibility by Application of Electromagnetic Stirring–

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Abstract

It appeared that electromagnetic stirring was very effective to improve the susceptibility of solidification cracking in weld metal of Al-2%Zn-3%Mg alloy with 0.24% zirconium. This beneficial effect of electromagnetic stirring was mainly due to the grain refinement of weld metal, but it was not seen for the alloys with less zirconium content than 0.24%.

KEY WORDS: (Solidification cracking) (Weld cracking) (Aluminum alloy) (Al-Zn-Mg alloy) (Zirconium) (Grain refinement) (Electromagnetic stirring) (GTA welding)

1. Introduction

In a previous report[1], it was made clear that zirconium addition to weld metal showed the most effective to improve the susceptibility of solidification cracking in weld metal of Al-Zn-Mg alloy among various additional elements and this beneficial effect of zirconium was closely related with grain refinement of weld-metal structure.

To say in detail, at more addition of zirconium than 0.36%, the weld-metal structure was fully changed to fine-equiaxed grains and then the susceptibility to solidification cracking was remarkably improved. At 0.24% of zirconium addition, however, the weld-metal structure consisted of the mixture of columnar and fine-equiaxed grains, because the grain-refining effect of zirconium was not so remarkable in this content. Therefore, in this case, the beneficial effect of zirconium to prevent the solidification cracking almost disappeared. However, even with same zirconium content, a very low crack susceptible weld bead was sometimes obtained when fine-equiaxed grains occasionally occupied the most part of weld bead.

It is very difficult to make aluminum alloy containing zirconium more than about 0.3% by current casting technique in commercial production. This means that the content of zirconium in weld metal is inevitably restricted to be less than about 0.3% in which content the effect of zirconium on grain refinement is not enough unfortunately.

As for the method of grain refinement of weld metal except for the addition of grain-refining elements, some other methods have been proposed[2], most of which were based on the artificial agitation of molten pool during welding.

Among them, the electromagnetic stirring with an aid of Lorentz force is considered to be the most effective method[3–6].

The authors also have confirmed its effectiveness on some aluminum alloy welds during GTA welding[7–9].

The purpose of this paper is to examine the effect of electromagnetic stirring not only on the grain refinement but also on the improvement of crack susceptibility of weld metal of Al-Zn-Mg alloy containing unsufficient zirconium content to refine the grains in weld metal.

2. Materials Used and Experimental Procedures

2.1 Materials used

The synthesized-weld-metal alloy which was used in the previous report[1] was again used, of which chemical composition was equivalent to that of weld metal of Al-4.5%Zn-1.2%Mg base metal (A7N01) welded by GMA

Table 1 Chemical compositions of materials used

Materials	Si	Fe	Mn	Mg	Cr	Zn	Zr	Ti	B
0.1 Zr	0.05	0.18	0.26	2.80	0.16	1.94	0.09	-	-
0.16 Zr	0.05	0.18	0.25	3.00	0.16	2.10	0.16	-	-
0.24 Zr	0.05	0.18	0.26	2.80	0.16	1.94	0.24	-	-
0.05 Ti+B	0.05	0.18	0.30	2.96	0.16	2.03	0.09	0.047	0.0071

† Received on April 28, 1984
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Transactions of JWRI is published by Welding Research Institute of Osaka University, Ibaraki, Osaka 567, Japan

welding with Al-5%Mg alloy filler wire (A5356). Nominal composition of synthesized-weld-metal alloy is Al-2%Zn-3%Mg-0.1%Zr with small amount of Si, Fe, Mn and Cr. Zirconium content was varied to 0.09, 0.16 and 0.24%. Besides these three zirconium containing alloys, titanium (with boron, Ti + B) containing alloy was also used. Chemical compositions of these materials used are shown in **Table 1**.

These alloys were homogenized by solution treatment after the casting, and then hot- and cold-rolled to 2 mm thick sheet and fully annealed.

2.2 Experimental procedures

2.2.1 Weld solidification cracking test

Cracking susceptibility of weld bead was evaluated by means of Houldcroft type cracking test and a tensile hot cracking test, the Vatra test (*Va*riable *T*ensile Deformation *Ra*te Hot Cracking Test) as the typical self-restraint and artificially-restraint cracking tests, respectively. In addition, the former can evaluate the crack susceptibility qualitatively, but the latter can evaluate it quantitatively by means of some criteria representing the characteristics of the ductility of solidifying weld metal.

The same test specimen as described in the previous report[1] was used for Houldcroft type cracking test (150 mm in length × 100 mm in width × 2 mm in thickness) and GTA(DCRP) bead-on-plate welding without filler wire was performed. The test specimen was set on a carriage traveling with a constant speed preset. The crack susceptibility of weld metal was evaluated by a percent ratio of crack length measured on weld-bead surface to the length of test specimen of 150 mm.

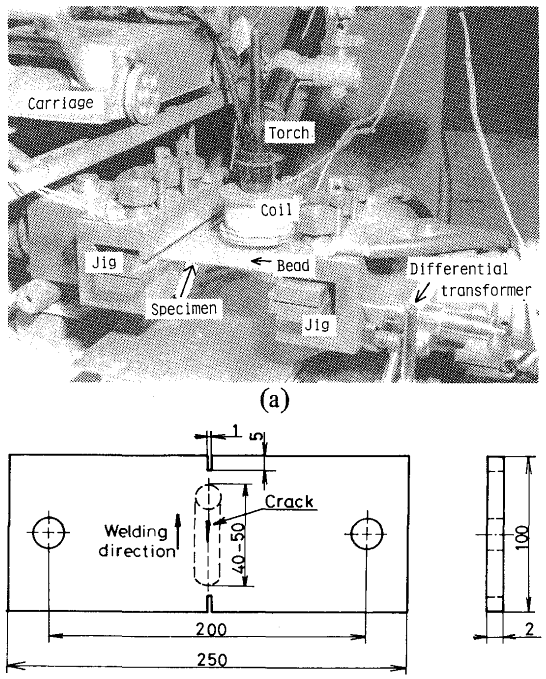

Fig. 1 (a) General appearance of Setup of a GTAW torch, a magnetic coil, a specimen to the Vatra tensile hot cracking tester,
(b) Shape and dimension of test specimen

On the other hand, **Figure 1 (a)** and **(b)** show a setup of the test specimen, GTA torch and a magnetic coil (Upper coil) for electromagnetic stirring and the dimension of test specimen of the Vatra hot cracking test to cracking tester, respectively. The test specimen of 250 mm in length, 100 mm in width and 2 mm in thickness was clamped to a chuck of tester by a pin and four bolts, the tip shape of which was circular cone, on each side of the specimen. Tensile deformation was applied on the specimen during welding with a preset constant tensile speed of crosshead between 0.01 and 3.5 mm/sec. In addition the tensile displacement of a crosshead applied on the test specimen was allowed to be changed between 0.1 and 1.5 mm with measuring it in aid of a differential transformer. Crack susceptibility of weld metal was evaluated by the criteria which were the BTR at rapid tensile speed about 3.5 mm/sec, and the critical tensile speed, $\dot{D}c$ and the minimum displacement, D_{min} required to cause cracking in weld metal. These criteria were considered to represent the characteristics of ductility of solidifying weld metal.

The welding condition used was 55A of welding current, 21 V of arc voltage and 150 mm/min of welding speed for each cracking test, and in addition, more high welding speed of 300 mm/min was employed with 70A and 21 V for Houldcroft type test.

These welding conditions were selected to obtain a two dimensional weld bead, the width of which were about 10 mm and almost equal on the top and back surfaces.

2.2.1 Electromagnetic stirring method

The principle of the electromagnetic stirring of weld pool during welding is based on Lorentz force caused by the interaction between welding current passing through molten weld metal and external magnetic field applied through weld pool perpendicularly to specimen surface. Details were described in the previous report[7]. Two types of magnetic coil, lower and upper coils, generating external magnetic field were utilized. The lower coil has a ferrous core and set under the specimen perpendicularly in line with GTAW torch. The upper coil has a hole in its center instead of a core and set to the tip of GTAW torch with inserting a tungsten electrode into a central hole.

As to the intensity of external magnetic field, the maximum intensity under the condition of making a smooth weld bead was adopted, because an excess intensity of magnetic field prevent the formation of a smooth

Table 2 Welding and electromagnetic conditions selected for weld cracking test

Cracking test	Welding condition			Condition of electromagnetic stirring	
	Welding current	Arc voltage	Welding speed	Frequency	Magnetic field
Houldcroft type test	55A 70A	21V 21V	150mm/min 300mm/min	2 - 20Hz 2 - 20Hz	175gauss 150gauss
the Vatra test	55A	21V	150mm/min	2Hz	150gauss

surface weld bead due to the too strong movement of molten metal in weld pool by intense Lorentz force[7], whose intensity depended on the magnitude of welding current.

The frequency of electromagnetic stirring was varied from 2 to 20 Hz at Houldcroft type test and a constant of 2 Hz at Vatra test as shown in **Table 2** where the intensity and frequency of magnetic field was tablated for each welding condition used.

3. Experimental Results

3.1 Effect of frequency of electromagnetic stirring to improve crack susceptibility

At first, the effect of electromagnetic stirring on the grain refinement and the improvement of crack susceptibility was examined by means of the Houldcroft type cracking test for 0.24%Zr containing alloy which seems to be the most probable alloy to be refined in grains according to the results in the previous report[1].

Figure 2 (a) and **(b)** show the test results which indicate the effect of the frequency of electromagnetic stirring on crack susceptibilities with a constant magnetic field of 175 and 150 gausses for the welding speeds of 150 and 300 mm/min respectively.

Zero Hz in abcissa represents the weld metal without stirring in this experiment.

Without stirring, weld metal showed much high crack susceptibilities in both welding speeds. However, by the application of electromagnetic stirring with frequencies of 2 and 5 Hz, crack susceptibilities were remarkably decreased on both welding speeds. When the frequency was increased more than 10 Hz crack susceptibility was again increased to almost the same or somewhat larger than that without stirring, though ocassionally it showed a very low value at 10 Hz.

These results clearly indicated that electromagnetic stirring of weld metal during welding was very effective to improve the crack susceptibility of 0.24%Zr containing Al-2%Zn-3%Mg alloy. Furthermore it was cleared that there was an adequate frequency range, that is, from 2 to 5 Hz in this experiment.

The macrostructural change of weld metal caused by electromagnetic stirring is shown in **Fig. 3** for the welding speed of 300 mm/min. Without stirring the weld metal consisted of coarse columnar structures as shown in Fig. 3 (a) showing solidification cracks along grain boundaries of these columnar grains.

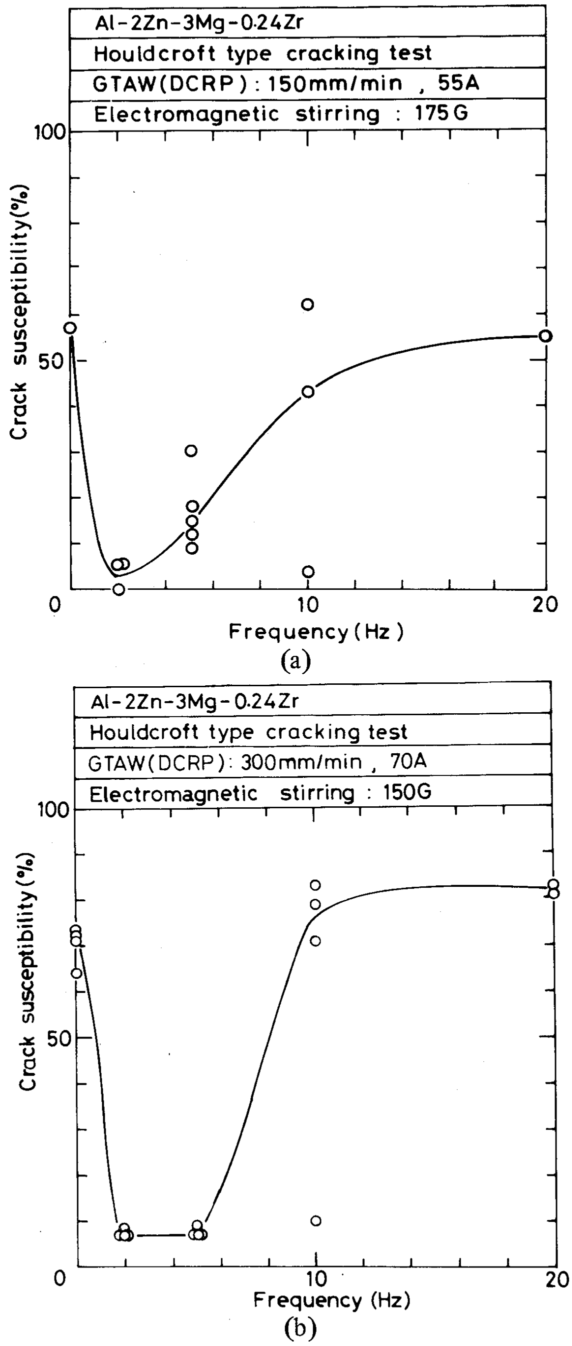

Fig. 2 Relation between crack susceptibility of weld metal and frequency of external magnetic field: (a) 150 mm/min, (b) 300 mm/min of welding speeds

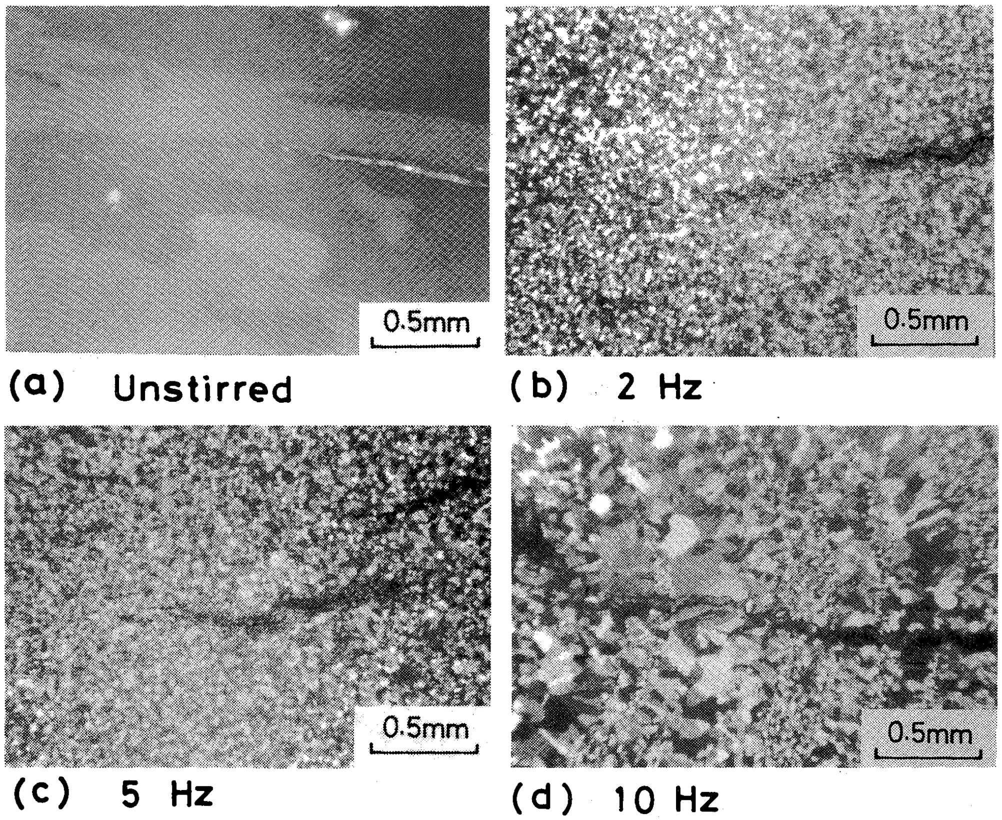

Fig. 3 Macrostructures of weld metal of 0.24%Zr containing Al-2%Zn-3%Mg alloy without and with electromagnetic stirring at various frequencies: 70A, 300 mm/min; 150 gauss; etched with Barker's reagent and polarized lighting

On the contrary, with electromagnetic stirring of 2 and 5 Hz in frequencies as shown in Fig. 3 (b) and (c), respectively, the grain structure of weld metal were extremely refined and changed to very fine-equiaxed grains throughout weld bead. The mean diameter of these equiaxed grains was about 18 to 23 μm. These values are almost the same measured in the weld metal of 0.36%Zr containing alloy which showed very low crack susceptibility with only the addition of zirconium and without any artificial stirring in the previous report[1].

Increasing the frequency to 10 Hz in Fig. 3 (d), however, the degree of the grain refinement became to be less than those at 2 and 5 Hz, though structures were much more refined in comparison with those without stirring. Moreover, as a noticiable matter, weld-metal structure showed a banded structure, that is, two zones consisted of columnar grains and fine-equiaxed grains alternately appeared, but the widths of these bands were irregular irrespective of the frequency of electromagnetic stirring.

With higher frequency than 10 Hz, these banded or mixed structures were also observed in weld metal, but colunmnar grains became dominant. The same dependency of structural change in weld metal on the frequency of electromagnetic stirring was observed at welding speed of 150 mm/min.

These structural examination reveal that the beneficial effect of electromagnetic stirring to improve crack susceptibility is mainly due to the grain refinement, and in addition to this, it is necessary that weld-metal structure is extremely and uniformly refined thoughout weld bead, otherwise this beneficial effect of electromagnetic stirring disappeares.

Moreover, **Figure 4** shows a typical example which shows more clearly the relationship between grain refinement and solidification cracking.

Upper in Fig. 4 shows an appearance of weld-bead surface tested by Houldcroft type cracking test at the welding speed of 300 mm/min. At first, test welding was performed without electromagnetic stirring and when the weld pool reached to the part surrounded with rectangular area in figure, electromagnetic stirring of 5 Hz and 150 gauss was started to be applied and it was continued until the finish of welding.

Lower figure shows a close-up microphotograph in the rectangular area, which shows the drastic change in structure of weld metal appeared at the instant of the application of electromagnetic stirring. Without stirring coarse columnar structure was clearly grown and solidification cracking was propagating along these grain boundaries. However, as soon as stirring was applied, weld-metal structure was suddenly changed to be very fine-equiaxed structure, and moreover, at the same time propagation of

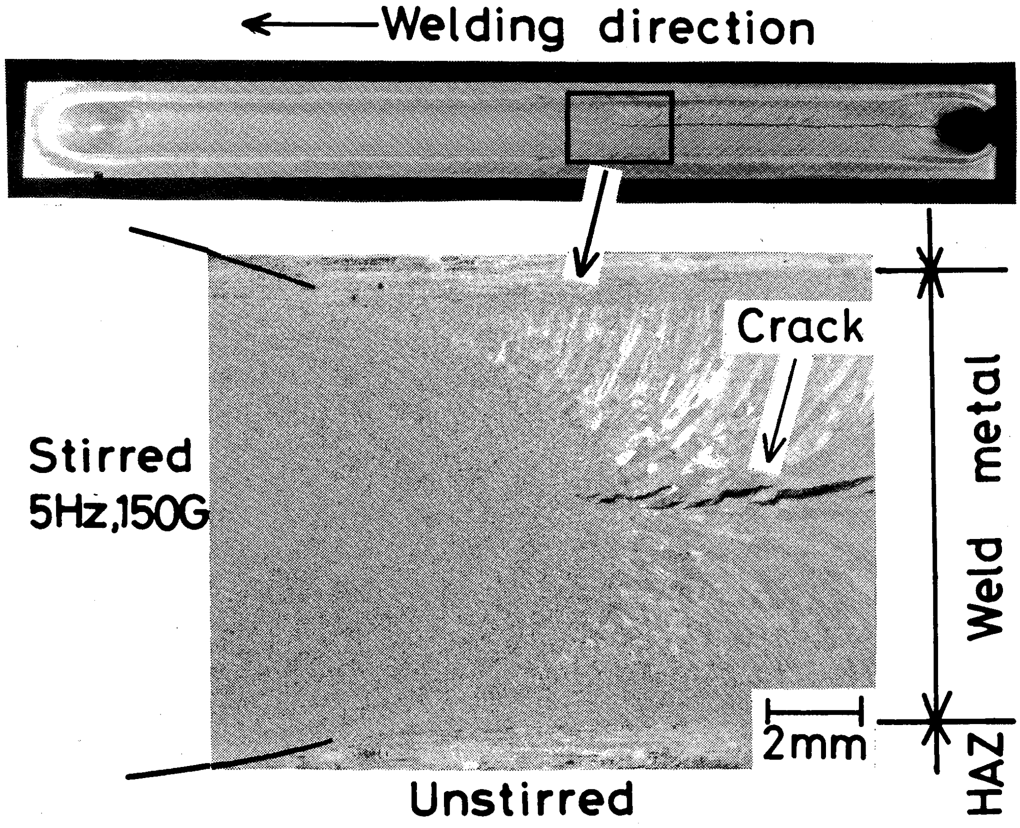

Fig. 4 General appearance of weld-bead surface showing macrostructural change caused by electromagnetic stirring applied on the way of welding: 70A, 300 mm/min; 5 Hz, 150 gauss

cracking was stopped at this point. Of course, if electromagnetic stirring was not applied or even if it was applied at more frequency than 10 Hz, solidification cracking was propagated away until near the finish of weld bead.

Consequently, it was clearly shown that even with same zirconium content, a columnar grain structure has no beneficial effect, on the contrary, a fine-equiaxed grain structure has beneficial effect to improve crack susceptibility of weld metal.

3.2 Minimum content of zirconium required to improve crack susceptibility in aid of electromagnetic stirring

Figure 5 shows the relation between crack susceptibilities and zirconium content in weld metal without and with electromagnetic stirring of 5 Hz in frequency and 150 gauss in magnetic field for the welding speed of 300 mm/min. Zirconium content in weld metal was varied to 0.09, 0.16 and 0.24%. In addition, titanium with boron (Ti + B) containing alloy (Al-2%Zn-3%Mg-0.1%Zr-0.05%Ti + B) was also tested in comparison with zirconium containing alloy.

Without electromagnetic stirring, all the alloys showd very high crack susceptibilities irrespective of zirconium content or Ti + B addition. In spite of the application of electromagnetic stirring under the most adequate condition in this experiment, only the 0.24%Zr containing alloy showed remarkable decrease in crack susceptibility.

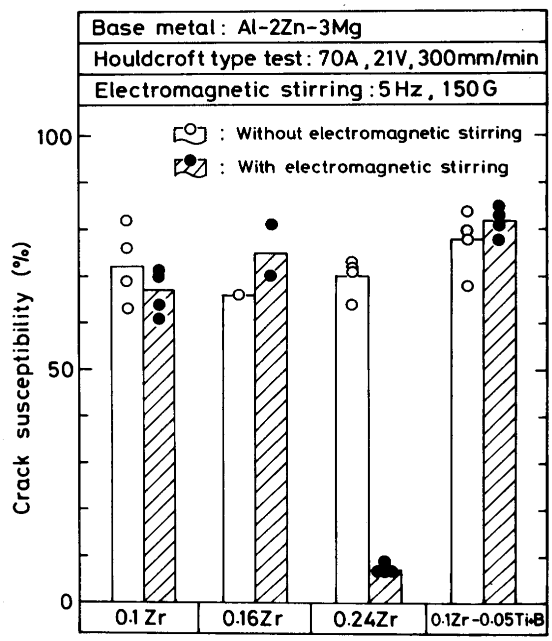

Fig. 5 Effect of electromagnetic stirring on crack susceptibility of weld metal with various zirconium and titanium (with boron) contents.

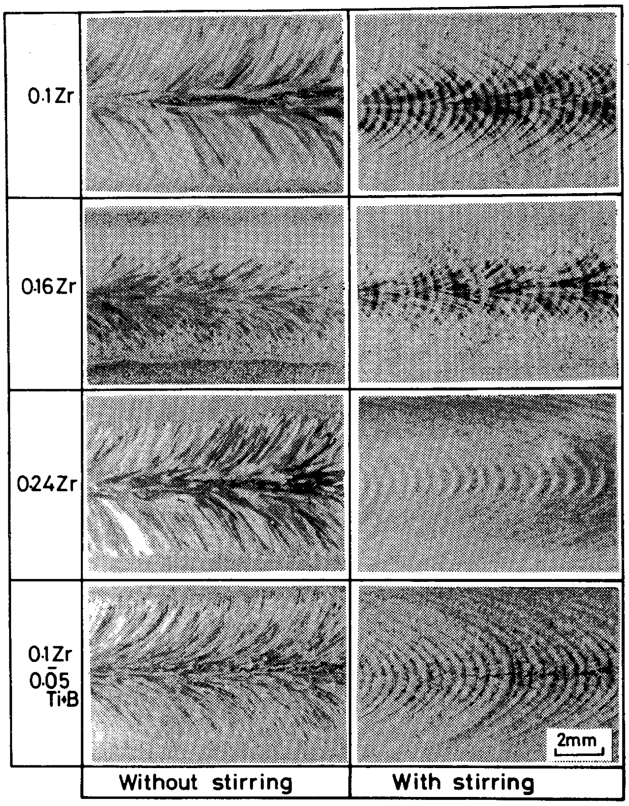

Fig. 6 Macrostructural changes on weld bead surface caused by electromagnetic stirring for the alloys with various zirconium and titanium (with boron) contents.

It appeared, unfortunately, that less zirconium content than 0.16% has no beneficial effect. 0.05%Ti + B addition also showed no beneficial effect.

Therefore the minimum content of zirconium required to reduce crack susceptibility associated with electromagnetic stirring was considered to be between 0.16 and 0.24%.

This threshold content of zirconium coincided with that required to cause the grain refinement in weld metal as shown in **Fig. 6** which shows the macrostructural changes occurred on the surface of weld metal by the application of electromagnetic stirring. Without stirring weld-metal structures of these alloys consisted of coarse columnar grains, though on 0.05Ti + B alloy they were slender. With electromagnetic stirring, the grain structure of each alloy became refined in some degree. However, the degree of grain refinement was much different with the alloys. That is, on 0.09 and 0.16%Zr containing alloys coarse columnar grains were still observed clearly near the center of weld bead, though considerable grain refinement was observed near fusion boundaries, especially on 0.16% Zr alloy weld. On the contrary, 0.24%Zr containing alloy showed very fine-equiaxed grains without any trace of columnar grains as mensioned previously. In case of 0.05%Ti + B alloy coarse columnar grains disappeared and changed to stray crystal or equiaxed grains, though their grain sizes were much larger in comparison with 0.24%Zr containing alloy.

3.3 Effect of electromagnetic stirring on critical tensile speed and minimum displacement required to cause cracking

It has been made clear qualitatively by Houldcroft type cracking test in section 3.1 and 3.2 that electromagnetic stirring was very effective to improve crack susceptibility of weld metal of 0.24%Zr containing alloy.

In order to confirm qualitatively this beneficial effect of electromagnetic stirring, the Vatra test was carried out without and with electromagnetic stirring under the condition of 2 Hz and 175 gauss at the welding speed of 150 mm/min.

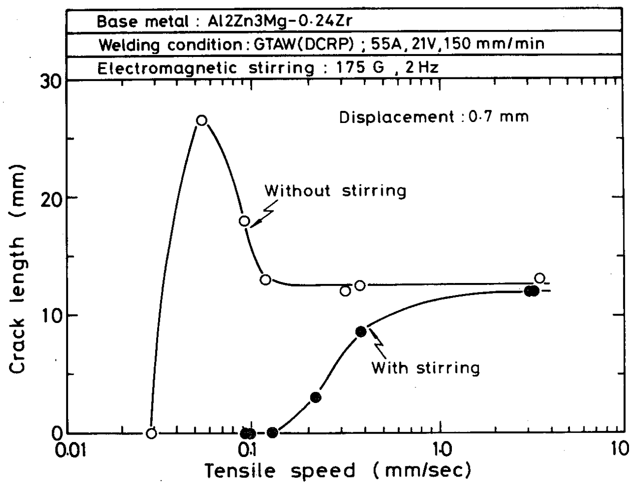

Fig. 7 Relation between crack length and tensile speed under a constant displacement of 0.7 mm for 0.24%Zr containing Al-2%Zn-3%Mg alloy with and without electromagnetic stirring.

Figure 7 shows the effect of tensile speed on crack length of longest crack measured on the surface of weld bead with a constant displacement of 0.7 mm.

At the rapid tensile speed of about 3.5 mm/sec, the crack lengths which were considered to represent the BTR were almost equal irrespective of electromagnetic stirring. This means that the BTR was not changed even with electromagnetic stirring.

However, the change in crack length against tensile speed was much different with electromagnetic stirring. Without stirring, as the decrease of tensile speed, crack length was increased, at first gradually and thereafter steeply, and then it suddenly fell to zero. This tensile speed is named the critical tensile speed required to cause cracking $\dot{D}c$. Inversely, with stirring, crack length was

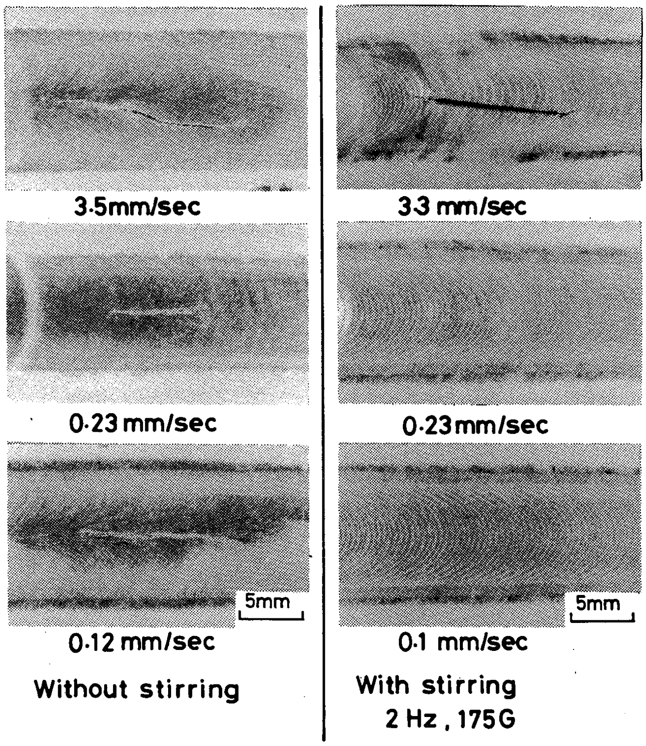

Fig. 8 General appearance of weld bead showing cracking caused by the Vatra tensile hot cracking test with various tensile speed under a constant displacement of 0.7 mm for 0.24%Zr containing Al-2%Zn-3%Mg alloy with and without electromagnetic stirring: 55A, 21 V, 150 mm/min; 2 Hz, 175 gauss

gradually decreased as the decrease of tensile speed. The reason why the crack length was changed with tensile speed will be discussed in the 4.2.

As to the $\dot{D}c$ value, it was 0.03 mm/sec without electromagnetic stirring, but by the application of electromagnetic stirring, it was much increased to 0.13 mm/sec, that is, 4 times larger than that without stirring. **Figure 8** shows the typical appearances of weld-bead surface showing cracking at different tensile speeds without and with electromagnetic stirring.

Nextly, in order to obtain the minimum displacement to cause cracking, D_{min}, the relation between crack length and the displacement was examined at a constant tensile speed of 0.23 mm/sec. Test results are shown in **Fig. 9**. Without stirring D_{min} was 0.22 mm, but with stirring, it was increased to 0.45 mm, two times of that without

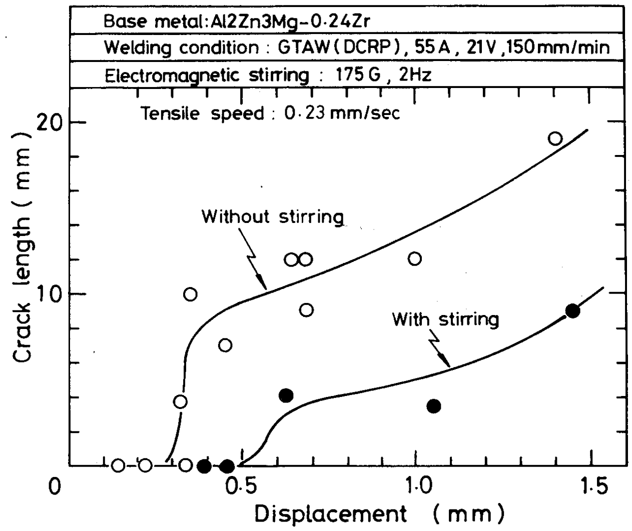

Fig. 9 Relation between crack length and displacement at a constant tensile speed of 0.23 mm/sec for 0.24%Zr containing alloy with and without electromagnetic stirring

stirring. Moreover, crack lengths with stirring were much shorter than those without stirring at any displacement.

Table 3 tablated the criteria obtained by the Vatra test for 0.24%Zr containing Al-2%Zn-3%Mg alloy in comparison with the case without and with electromagnetic stirring.

Judging from these results, the grain-refined weld metal by electromagnetic stirring showed much large D_{min} value and much high $\dot{D}c$ value than those of the coarse-grain weld metal without electromagnetic stirring, though the BTR value was not changed with electromagnetic stirring.

Consequently, it is considered that the increase in $\dot{D}c$ and D_{min} values are the main reason of the beneficial effect of electromagnetic stirring to improve the susceptibility of solidification cracking for 0.24%Zr containing Al-2%Zn-3%Mg alloy.

4. Discussions

4.1 Microstructural changes in weld metal caused by electromagnetic stirring

Figures 10 and **11** show the typical microstructures of weld metals of 0.1%Zr containing alloy without electromagnetic stirring and of fine-equiaxed weld metal of

Table 3 Criteria of BTR, $\dot{D}_c$ and D_{min} obtained by the Vatra tensile hot cracking test for 0.24%Zr containing Al-2%Zn-3%Mg alloy with welding condition of 55A, 21V, and 150 mm/min with and without electromagnetic stirring of 2 Hz, 175 gauss.

	Brittleness temperature range* BTR(°C)	Critical tensile speed for crack initiation**, $\dot{D}_c$(mm/sec)	Minimum ductility for crack initiation***, D_{min} (mm)
Without electromagnetic stirring	180	≈0.03	0.22
With electromagnetic stirring (175G, 2Hz)	175	≈0.13	0.45

* at 3.5mm/sec tensile speed and 0.7mm displacement
** at 0.7mm displacement
*** at 0.23mm/sec tensile speed

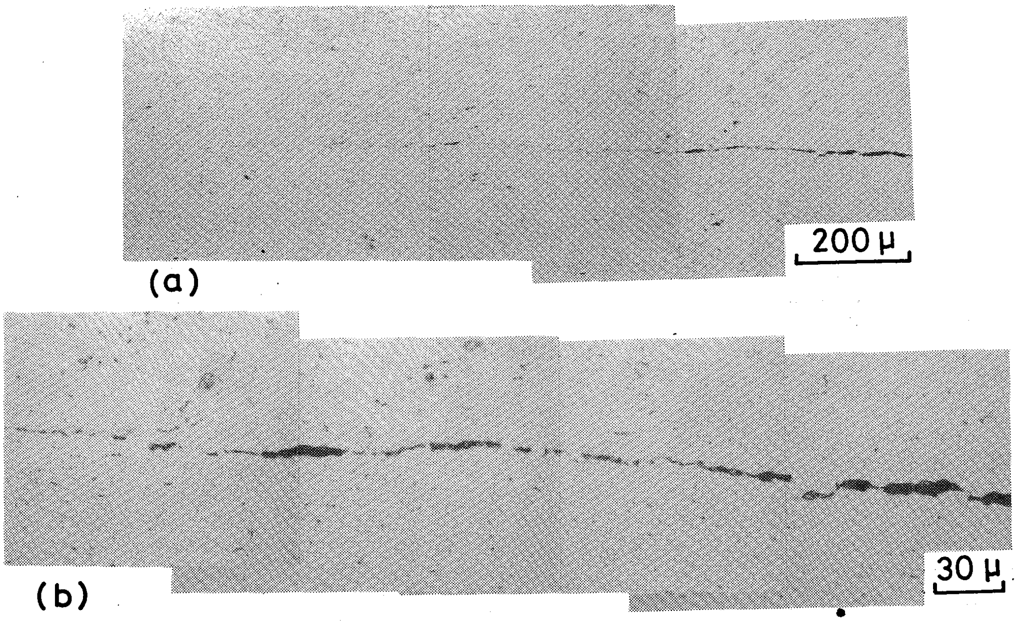

Fig. 10 Microstructure of weld metal of Al-2%Zn-3%Mg-0.1%Zr alloy without electromagnetic stirring, showing tip of cracking caused by Houldcroft type cracking test: 70A, 300 mm/min; etched with Barker's reagent

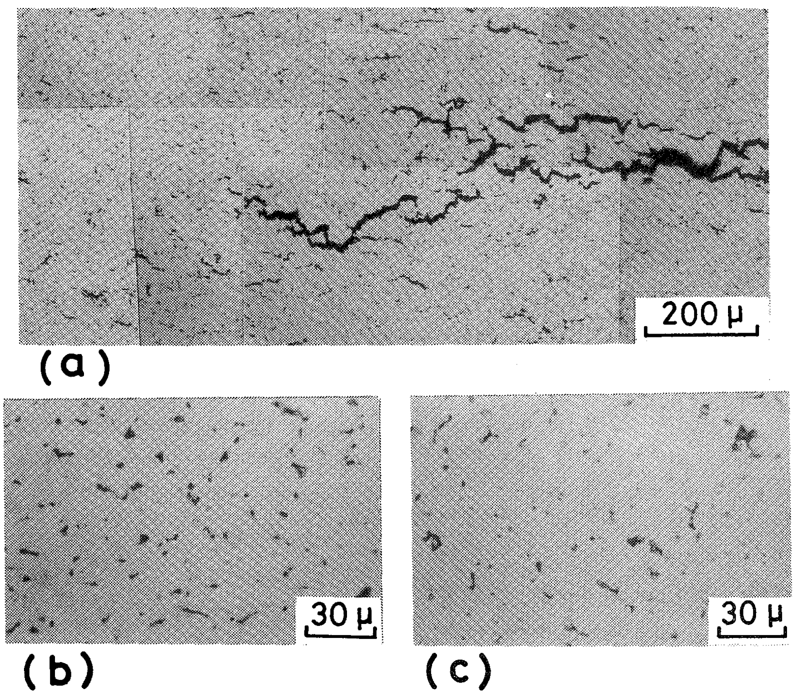

Fig. 11 Microstructure of weld metal of Al-2%Zn-3%Mg-0.24%Zr alloy with electromagnetic stirring, showing tip of cracking caused by Houldcroft type cracking test: 70A, 300 mm/min; 5 Hz, 150 gauss; etched with Barker's reagent

0.24%Zr containing alloy with electromagnetic stirring, respectively, near the end of cracking caused by Houldcroft type cracking test.

As shown in Fig. 10 (a) a crack was propagated almost straight along grain boundary of a coarse columnar grain, and film-like eutectic products, which seemed to represent the remaining liquid at the last stage of solidification process, were observed on their grain boundaries as seen in Fig. 10 (b). On the contrary, in case of fine-equiaxed grain structure, the tip of the crack branched off in many grain boundaries as shown in Fig. 11 (a), and in addition, eutectic products were dispersed globularly in grain boundaries as seen in Fig. 11 (b) and (c).

These results suggested that fine-equiaxed grain structures inclined to promote not only the redistribution of the strain or deformation applied but also the redistribution of the remaining liquid into may grain boundaries.

It is considered that these microstructural characteristics associated with fine-equiaxed grain structure is undoubtedly advantageous to improve the crack susceptibility of weld metal.

4.2 Relation between tensile speed and crack length at the Vatra tensile hot cracking test

There was a quite different relation between crack length and tensile speed appeared in Fig. 7 even at the same alloy, when the microstructures of weld metal were only changed from coarse columnar to fine-equiaxed grains.

According to a theoretical analysis in the previous report[10], crack length is represented by following formula under some assumptions:

$$L = L_B + V\left(\frac{\epsilon_u - 2\epsilon_{min}}{\dot{\epsilon}}\right) \quad (1)$$

where L: crack length of longest crack
L_B: crack length at rapid straining rate, corresponding to the BTR
V: welding speed
ϵ_u: augmented strain or displacement
ϵ_{min}: minimum ductility or displacement to cause cracking
$\dot{\epsilon}$: straining rate or tensile speed

From this equation next conclusions are able to be drawn: When $\epsilon_{min} < (1/2)\epsilon_{u'}$, crack length, L is increased as the decrease of straining rate, $\dot{\epsilon}$, inversely, when $\epsilon_{min} > (1/2)\epsilon_u$, L is decreased as the decrease of $\dot{\epsilon}$.

Now let discuss about the test results in Fig. 7, L_B was corresponding to the BTR, that is, the crack length at rapid tensile speed at about 3.5 mm/sec. Therefore, this value is not changed irrespective of electromagnetic stirring. ϵ_u is a constant of 0.7 mm of the displacement. Supposing that D_{min} value obtained in Fig. 9 at 0.23 mm/sec of tensile speed is applicable as the ϵ_{min} value in equation (1). Without electromagnetic stirring, as $D_{min}(\epsilon_{min})$ is 0.22 mm, that is, $\epsilon_{min} < (1/2)\epsilon_u$, L should increased as the decrease of $\dot{\epsilon}$. With electromagnetic stirring, as Dmin was increased to 0.45 mm, that is, $\epsilon_{min} > (1/2)\epsilon_u$, L should be decreased as the decrease of $\dot{\epsilon}$.

These predictions about the relation between crack length and $\dot{\epsilon}$ showed a good agreement with the test results as shown in Fig. 7.

4. Conclusions

The susceptibility of solidification cracking in weld metal of zirconium containing Al-2%Zn-3%Mg simulate alloy which is equivalent to weld metal of A7N01 base metal with Al-5%Mg filler wire has been investigated by means of Houldcroft type cracking test and the Vatra tensile hot cracking test, and the effect of electromagnetic stirring of weld metal during welding to improve the crack susceptibility was examined.

Main conclusions obtained are as follows:

(1) Electromagnetic stirring of weld metal during welding was very beneficial to improve the susceptibility of solidification cracking of weld metal of 0.24%Zr containing Al-2%Zn-3%Mg alloy. This beneficial effect was mainly due to grain refinement of weld metal.

(2) In case of 0.24%Zr containing alloy, the weld metal consisted of coarse columnar grain structure without electromagnetic stirring showed very high crack susceptibility. On the contrary, fine-equiaxed grain weld metal caused by electromagnetic stirring showed very low crack susceptibility even at the same zirconium content.

(3) The optimum frequency of external magnetic field in electromagnetic stirring for improvement of crack susceptibility was 2 to 5 Hz. This optimum frequency range coincided with that for the grain refinement in weld metal.

(4) No grain refinement and no improvement of susceptibility of cracking was observed in the weld metal containing zirconium less than 0.16% by means of Houldcroft type cracking test. 0.24% of zirconium content in weld metal was required to cause grain refinement and improvement of crack susceptibility in this experiment.

(5) The brittleness temperature range of 0.24%Zr containing alloy was not changed irrespective of electromagnetic stirring. Critical tensile speed and minimum displacement required to cause cracking were, however, increased about 4 and 2 times, respectively, by macrostructural change from coarse columnar to fine-equiaxed grains in aid of electromagnetic stirring.

Acknowledgement

The authors would like to express their thanks to Mr. Takeshi Serada, formerly student of KINKI Univ. for his helpful assistance in this study.

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